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## MULTIPOLARITY OF QUASICONTINUUM $\gamma$ -RAYS FROM COLLECTIVE HIGH-SPIN STATES IN $^{152}\text{Dy}$

H.J. RIEZEBOS, A. BALANDA<sup>1</sup>, J. DUDEK<sup>2</sup>, J. VAN KLINKEN, W. NAZAREWICZ<sup>3</sup>, Z. SUJKOWSKI<sup>4</sup> and M.J.A. DE VOIGT

*Kernfysisch Versneller Instituut, Zernikelaan 25, NL-9747 AA Groningen, The Netherlands*

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Measured internal conversion coefficients for quasicontinuum transitions in  $^{152}\text{Dy}$  in the spin range of 30–50 establish their predominantly stretched E2 character. Those transitions are attributed to triaxial bands near the yrast line as calculated in terms of the cranking approximation using the Woods–Saxon potential.

The nucleus  $^{152}\text{Dy}$  has been the subject of many experimental as well as theoretical investigations since the discovery of a high-spin ( $17^+$ ) isomer in 1976. The nearly spherical shapes at low spin have been inferred from the irregular energy level scheme established up to spin 38 already in 1979. The presence of several isomers established the predominantly non-collective nuclear motion at low and moderately high spins; see ref. [1] for a summary of the early investigations on  $^{152}\text{Dy}$ . An extensive experimental study [2] of the quasicontinuum (qc) spectrum did not reveal any evidence for collective behaviour up to spin 30. Therefore the exciting possibility of a drastic shape change from oblate to prolate has been searched for in the domain of very high spins [3,4]. Recently a discrete SD band has been located [5] up to spin 60 in  $^{152}\text{Dy}$ . Some evidence for spherical to deformed shape changes has also been deduced [6–8] for  $^{152}\text{Dy}$  from the behaviour of “bumps” in the  $\gamma$ -ray spectra and from the derived multiplicity-energy correlations.

We report predominantly stretched E2 transitions in the spin range 30–50, measured with a mini orange spectrometer [9], which are interpreted in terms of near-yrast triaxial bands employing the cranking approximation.

The quasicontinuum high-spin states in  $^{152}\text{Dy}$  were selected after 180 MeV  $^{40}\text{Ar}$  induced reactions by using a sum spectrometer and by applying the catcher-foil technique. As a cross-check the experiment was repeated with a  $^{12}\text{C}$  beam of 82 MeV. The maximum angular momentum transferred in the first reaction is  $l_{\text{max}} = 70\hbar$  and in the second reaction  $\approx 40\hbar$ , as deduced from measured multiplicities.

Self-supporting targets of 700  $\mu\text{g}/\text{cm}^2$  enriched  $^{144}\text{Nd}$  and  $^{116}\text{Cd}$  were used. Transitions deexciting the  $17^+$ , 60 ns, isomer in  $^{152}\text{Dy}$  were detected in an array of four  $7.6 \times 5.1$  cm  $\varnothing$  NaI detectors located near the catcher. The target was placed in the center of a  $40 \times 40$  cm  $\varnothing$  NaI sum spectrometer divided into halves of three segments each. The sum energy (efficiency  $\sim 55\%$ ) and segment-fold were also used to select the entry region as well as to decrease the contribution of  $^{151}\text{Dy}$ , in which also isomeric transitions occur, to less than 10%. We measured the energy and angular distributions of prompt gamma rays from states above the isomer with three  $15.1 \times 12.6$  cm  $\varnothing$  NaI detectors placed at 50 cm distance from the target at angles of  $90^\circ$ ,  $135^\circ$  and  $165^\circ$  to determine the  $\gamma$ -ray

<sup>1</sup> Jagiellonian University, PL-30-059 Cracow, Poland.

<sup>2</sup> Centre de Recherches Nucléaires et Université Louis Pasteur, F-67037 Strasbourg Cedex, France.

<sup>3</sup> Institute of Physics, Warsaw Institute of Technology, PL-00-662 Warsaw, Poland.

<sup>4</sup> Institute for Nuclear Studies PL-05-400 Otwock, Swierk, Poland.

energies and angular distributions. Neutrons were rejected by time-of-flight discrimination. Two Ge detectors, surrounded by BGO anti-Compton shields, were used to check the exit channel selectivity and to measure the yields of discrete lines. Prompt conversion electrons were measured with a mini orange spectrometer [9] placed in the gap between the two halves of the sum spectrometer at  $60^\circ$  with respect to the beam direction.

The unfolded  $\gamma$ -ray spectra measured in the  $^{144}\text{Nd}(^{12}\text{C}, 4n)$  and  $^{116}\text{Cd}(^{40}\text{Ar}, 4n)$  reactions are shown in fig. 1a. The corresponding  $\gamma$ -ray anisotropies (fig. 1b) in the  $^{40}\text{Ar}$  experiment are close to the value expected for stretched quadrupole transitions between fully aligned high-spin states

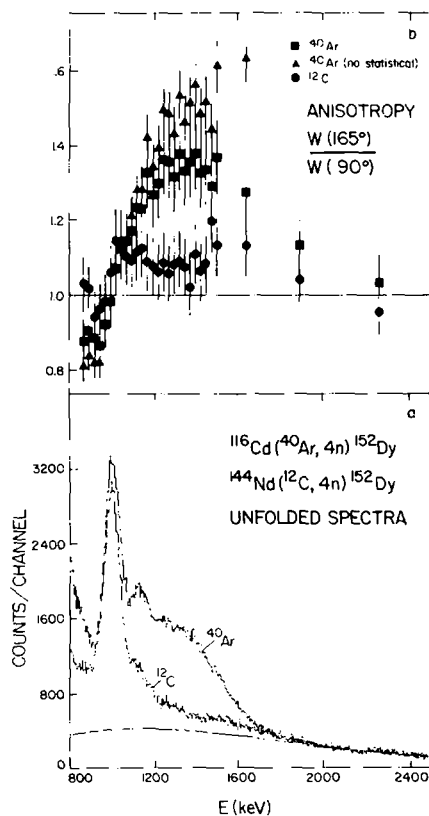


Fig. 1. (a) Unfolded  $\gamma$ -ray spectra of the  $^{144}\text{Nd}(^{12}\text{C}, 4n)$  and the  $^{116}\text{Cd}(^{40}\text{Ar}, 4n)$  reactions producing  $^{152}\text{Dy}$ . (b) The corresponding  $\gamma$ -ray anisotropies defined as the  $\gamma$ -ray yield at  $165^\circ$  divided by the corresponding yield at  $90^\circ$ . Triangles show the anisotropy of the qc transitions for the  $^{40}\text{Ar}$  reaction with the statistical transitions subtracted from the total  $\gamma$ -ray yield.

( $a_2 = 0.38$ ,  $a_4 = -0.13$ ), when the (isotropic) statistical E1 contribution is subtracted. The statistical distribution is approximated by  $\sim E^3 \times \exp(E/kT)$  with  $kT = 0.38$  MeV (full line in fig. 1a). In the case of the  $^{12}\text{C}$  experiment only small fractions,  $< 20\%$ , of stretched quadrupole transitions are present. The conversion detectors were measured with two different magnet configurations of the mini orange spectrometer.

One setting with 5A type magnets (5A) had maximum transmission around 1150 keV, the other with the 6A type magnet (6A) around 1750 keV. The distance of the Si(Li) detector from the target was 70 mm in the 5A setting and 90 mm in the 6A setting. The background resulting from  $\gamma$ -rays and neutrons from the target and also from secondary electrons emitted by the surrounding material (such as the magnets and central absorber) was determined in a separate inbeam measurement with the same magnet configurations, but with a transmission setting outside the regions of interest (cf. ref. [10]). The ICC deduced after electron background subtraction are presented in fig. 2a along with the theoretical values for E1, E2 and M1. The consistency of the method was checked by determining the ICC of two discrete lines with energies of 968 keV (E1) and 991 keV (E2) (crossed data points in the figure). The prompt electron spectrum and the corresponding corrected and smoothed background curve measured with the  $^{40}\text{Ar}$  induced reaction are shown in fig. 2b. The 5A transmission curve is plotted in fig. 2c. In the  $^{40}\text{Ar}$  reaction the total ICC are quite close to the values expected for E2 transitions, particularly in the energy region around  $E_\gamma \sim 1$  MeV. Note that also E1/M1 admixtures can explain the measured ICC. The observed anisotropies (fig. 1), however, would then be consistent only if non-stretched M1 transitions were assumed, which seems unlikely for high energy  $\gamma$  rays ( $E_\gamma > 1$  MeV). The results obtained with the  $^{12}\text{C}$  beam indicate a nearly pure E1 character of the medium spin qc with less than 25% contribution coming from radiation with higher ICC, like E2. We can therefore attribute the high ICC observed with  $^{40}\text{Ar}$  beam to the deformed structures in the high-spin region of  $^{152}\text{Dy}$ .

The total prompt multiplicity of the qc bump

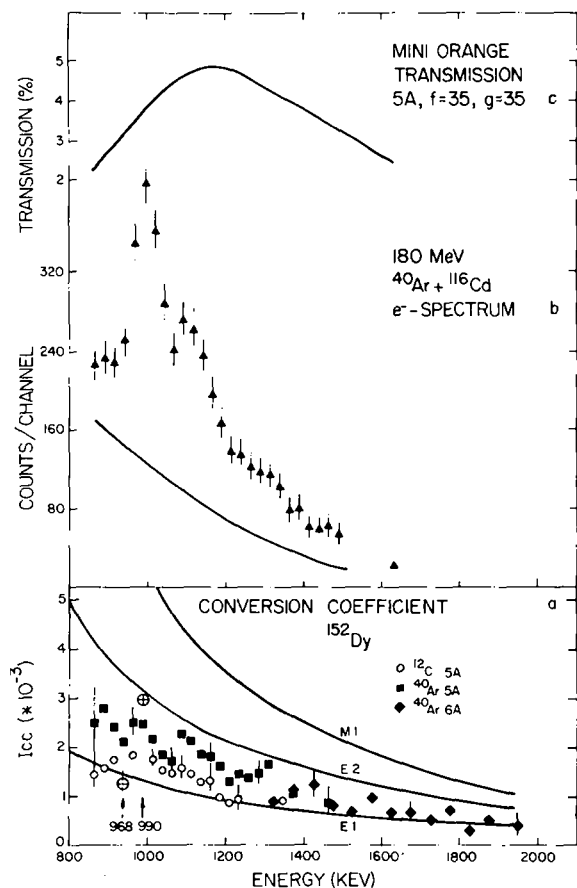


Fig. 2. (a) Measured internal conversion coefficients for the  $^{116}\text{Cd}(^{40}\text{Ar}, 4n)$  reaction (squares for the 5A mini orange setting and triangles for the 6A setting) and for the  $^{144}\text{Nd}(^{12}\text{C}, 4n)$  reaction (open circles). Positions and measured ICC of the 968 keV (E1) and 990 keV (E2) are indicated for the  $^{12}\text{C}$  induced reaction. (b) The electron spectrum measured with the Si(Li) detector and the deduced background (solid curve) are shown in the center part while the 5A transmission curve is shown in the top part (c);  $f$  denotes the distance between target and the center of the magnet and  $g$  that between the detector and that center.

deduced from the decomposition of the  $\gamma$ -ray spectrum in the  $^{40}\text{Ar}$  induced reaction into statistical, qc and discrete components is about 6 in the energy region 850–1500 keV. From a recent measurement [11] it is concluded that only a small intensity of less than 10% in the collective E2 bump (850–1500 keV) can be accounted for by superdeformed structures in the high-spin region of  $^{152}\text{Dy}$ . If we assume a similar population of the

discrete SD band in  $^{152}\text{Dy}$  as in the experiment of ref. [5], then only 4% intensity of the collective bump can be ascribed to that SD band. This number is derived from the 2.2% intensity of the SD band, combined with an average multiplicity of 11 between 850–1500 keV, giving a  $2.2 \cdot 11 = 24\%$  probability of one SD transition, compared to the 6 transitions observed in the qc bump. The total prompt multiplicity above the  $17^+$  isomer amounts to 23 for the  $^{40}\text{Ar}$  induced reaction. A detailed check of the known level scheme results in an average of 10 discrete transitions above the isomer, which carry a total amount of angular momentum of  $15\hbar$ . The decomposition of the full energy spectrum (cf. fig. 1a) results in an average of 3 statistical transitions and of the remaining 10 qc transitions we find 6 in the collective bump (see above). We assume for the angular momentum release  $0.5\hbar$  per statistical transition as well as  $0.5\hbar$  per neutron,  $2\hbar$  per transition in the collective bump and  $1\hbar$  for the remaining qc transitions. The total average angular-momentum release in the  $^{40}\text{Ar}$  reaction can now be estimated as

$$\langle l \rangle = (17 + 15 + 3 \cdot 0.5 + 6 \cdot 2 + 4 \cdot 1 + 4 \cdot 0.5) = 51.5\hbar.$$

The maximum angular momentum transfer is estimated as  $l_{\text{max}} \approx 65\hbar$  within the sharp cut-off approximation, taking into account a 20% contribution of the cross section of the 5n reaction. Relaxing the crude sharp cut-off restriction we may expect a population of states with angular momenta up to  $\sim 70\hbar$ .

Total-energy calculations (not discussed in detail here), which include the temperature effect, indicate the existence of optimal conditions for populating SD states. In  $^{152}\text{Dy}$  this corresponds to  $I_{\text{optimal}} \approx 70\hbar$  in the temperature range of  $T \approx 600$ –1000 keV. At that angular momentum a potential barrier separates the SD configuration from the non-SD ones. Within that temperature range a lower angular-momentum limit ( $I_{\text{limit}} \approx 60\hbar$ – $65\hbar$ ) is predicted below which the barrier disappears. In the reaction with the  $^{40}\text{Ar}$  beam we bring into the compound system  $l_{\text{max}} \approx 70\hbar$  and thus we may expect that only a small fraction of the total population feeds the SD states. This

result is confirmed by the 4% intensity, discussed above.

The  $\gamma$  transitions at the upper edge of the collective bump (cf. fig. 1a) with  $E_\gamma(\text{max}) \approx 1.5$  MeV, correspond to  $I_{\text{max}} \approx 48\hbar$ – $56\hbar$ , if we assume that they belong to triaxial bands with properties resulting from theory (see below). The energy region of  $E_\gamma = 850$ – $1400$  keV, where the high ICC are measured for the stretched E2 transitions, thus corresponds to the angular-momentum range of approximately  $30\hbar$ – $50\hbar$ .

We performed total energy calculations using the Woods–Saxon cranking method with the recent extension [12] of the shell correction approach generalized to the case of rotation. This enables us to separate individual particle–hole configurations. The quantum numbers characterizing these configurations are the parity  $\pi$ , and the signature  $r$ . The approach was earlier employed [13] to describe the shape evolution in the neutron-deficient Gd, Dy, Er and Yb isotopes. Here,

particular attention is paid to the collective structures around  $I \sim 50\hbar$  which are found in the present experimental study.

The results of calculations for the low-lying configurations in  $^{152}\text{Dy}$ , are shown in fig. 3. Each rotational band, represented by a single line in the figure, corresponds roughly to a constant deformation. Due to the centrifugal stretching the yrast oblate-shape polarization varies from  $-0.16 \leq \beta_2 \leq 0$  at  $I < 40\hbar$  to  $\beta_2 \approx -0.3$  at  $I > 50\hbar$ . At spins around 40 the non-collective particle–hole (p–h) yrast states contain usually two  $i_{13/2}$  neutrons and four  $h_{11/2}$  protons. Collective bands illustrated in fig. 3 lie 0.5–1.0 MeV above the p–h states. For  $I \sim 20\hbar$  the near-prolate bands with  $\beta_2 = 0.22$  and  $\gamma = 0^\circ$  appear close to the yrast states. The second group of collective bands, appearing close to the yrast for  $20 \leq I \leq 50$  are the triaxial configurations ( $10^\circ \leq \gamma \leq 25^\circ$ ,  $0.15 \leq \beta_2 \leq 0.23$ ). These bands contain the same characteristic  $2\nu i_{13/2}$  and  $4\pi h_{11/2}$  configurations as the non-collective yrast

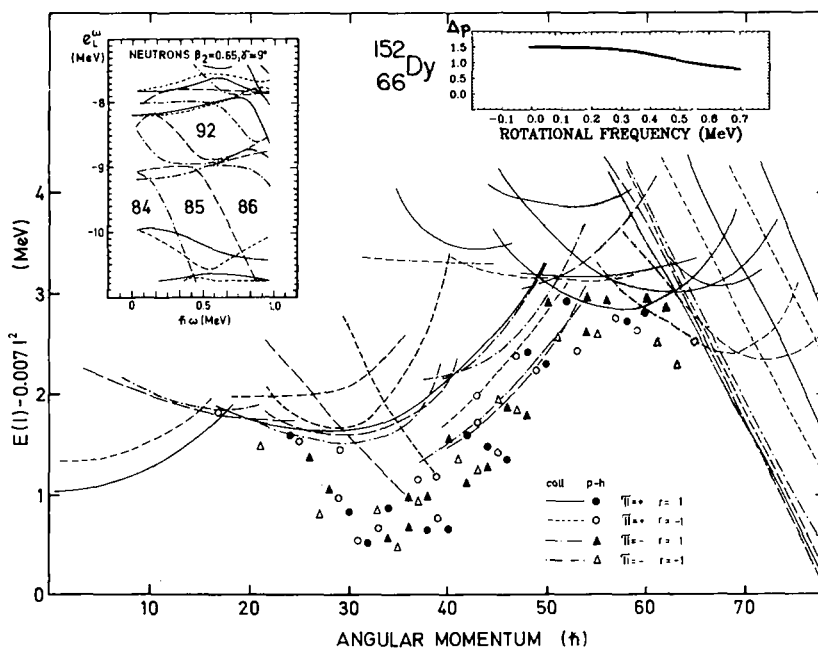


Fig. 3. Calculated excitation energies of near yrast structures in  $^{152}\text{Dy}$  displayed versus angular momentum. The excitation energies are taken with respect to a smooth reference,  $E_{\text{ref}} = 0.007 I^2 \text{ MeV}^{-1} \hbar^2$ . The single collective bands are indicated by lines and the particle–hole states by dots and triangles. The strongly sloping-down lines on the right represent the superdeformed bands, which extend to lower angular momentum above the yrast. The hatched area indicates the effect of proton pairing (see text). The upper-left inset shows the single-neutron routhians at the SD minimum ( $\beta_2 \approx 0.65$ ) as functions of rotational frequency. The variation with  $\omega$  of the proton-pairing gap,  $\Delta_p$  (in MeV) at that minimum, is shown in the upper-right inset.

states in the considered spin interval. With increasing rotational frequency these bands terminate, like those terminating at the non-collective states  $36^-$  and  $39^+$  (see fig. 3). In the spin interval  $45 \leq I \leq 70$  the bands with  $\beta_2 \approx 0.35$  and pronounced triaxiality ( $\gamma \approx 20^\circ$ ) appear close to the yrast. They differ from the bands in the previous group by the presence of one  $j_{15/2}$  neutron and/or one  $i_{13/2}$  proton. The superdeformed bands with  $\beta_2 \approx 0.65$  contain on the average two  $j_{15/2}$  neutrons and four  $i_{13/2}$  protons. The inset on the left in fig. 3 shows single-particle neutron routhians at deformation  $\beta_2 \approx 0.65$ . The large (more than 1 MeV) shell openings at  $N = 85, 86$ , in the single-neutron routhians (left inset), are the microscopic origin of the particular lowering of superdeformed bands in  $^{152}\text{Dy}$  and  $^{154}\text{Er}$  [13]. Calculations with pairing included indicate, however, that a significant contribution from the protons should be expected even as high as  $I \sim 60\hbar$ . This leads to a lowering of one of the superdeformed bands with respect to the others, typically  $\sim 800$  keV, thus producing a significant gap in the band structure (marked by the hatched area in fig. 3). The variation of  $\Delta_p$  (right inset) follows from the Hartree-Fock-Bogolyubov cranking calculations (cf. ref. [1]) with standard parameter values. At  $\hbar\omega = 0.7$  MeV the proton pairing gap is still of the order of 800 keV.

In summary, we observe a predominant amount of stretched E2 radiation at high angular momentum ( $\geq 30\hbar$ ) which is attributed to a number of triaxial rotational bands on the basis of a deformed Woods-Saxon cranking calculation. The stretched E2 character is unambiguously established by combining  $\gamma$ -ray anisotropies with internal conversion coefficients. From the measured intensities it can be concluded that only a minor fraction of the observed E2 bump can be accounted for by superdeformed structures.

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*Note added in proof.* We found also a strong deformation-driving effect due to neutrons, when minimizing the total energy with respect to the hexadecapole degree of freedom; a minimum at spin 50,  $\beta_4 \approx 0.09$ . The proton-energy gap reaches  $\approx 700$  keV and the static proton pairing collapses, resulting in a gap of also  $\approx 700$  keV between yrast and non-yrast SD states.

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